Auditory perception: **The near and far of sound localization**

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Most experiments on auditory localization have been concerned with the horizontal and vertical positions of sound sources. Recent studies have cast new light on the basis for judging the third dimension – source distance.

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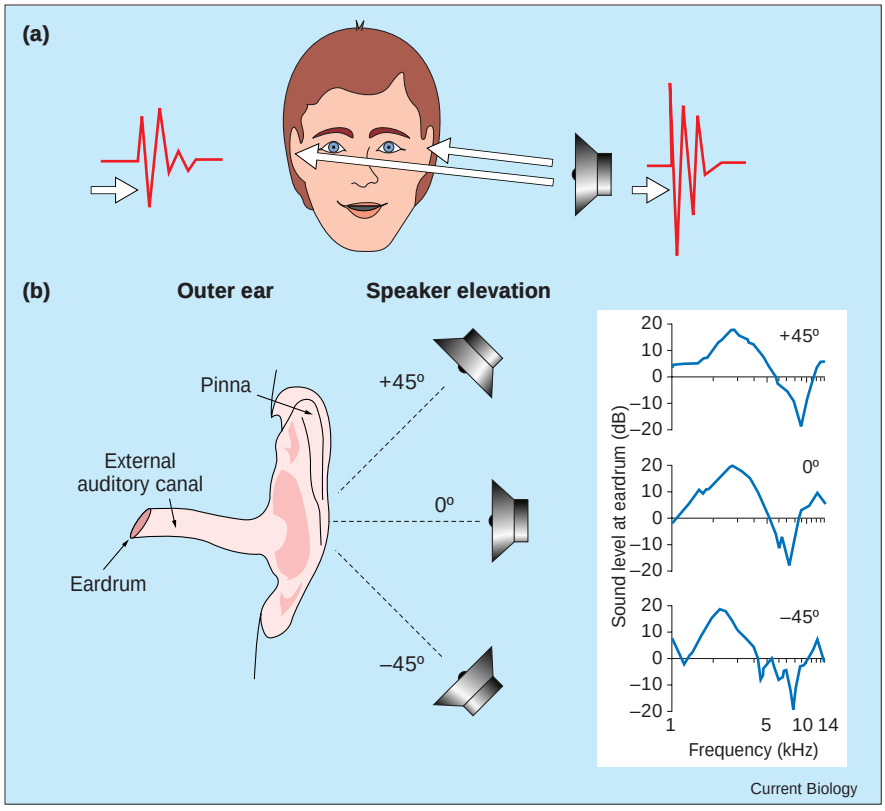
Spatial hearing has long been a major interest of auditory scientists. From the proposal early this century by Lord Rayleigh [1] that our perception of sound location is based on a comparison of the time of arrival and level of the sound at the two ears, to modern demonstrations of virtual, externalized sounds presented through headphones, this interest has almost exclusively been focused around the horizontal and vertical positions of sounds. The third dimension — distance — has been largely ignored, despite some early study by another pioneer of auditory science, Georg von Békésy [2]. Two recent papers [3,4] have breathed new life into this important, but neglected dimension of spatial hearing. Bronkhorst and Houtgast [3] have shown, using virtual sound technology, that the perception of sound distance in an enclosed room by human listeners can be quite simply modelled by fitting a temporal window around the ratio of direct-to-reverberant sound energy. And Graziano *et al.* [4] have shown that neurons in the frontal cortex of monkeys respond preferentially to sounds presented at particular near distances, within a hand grasp of the monkey's head.

Distance cues in an enclosed space

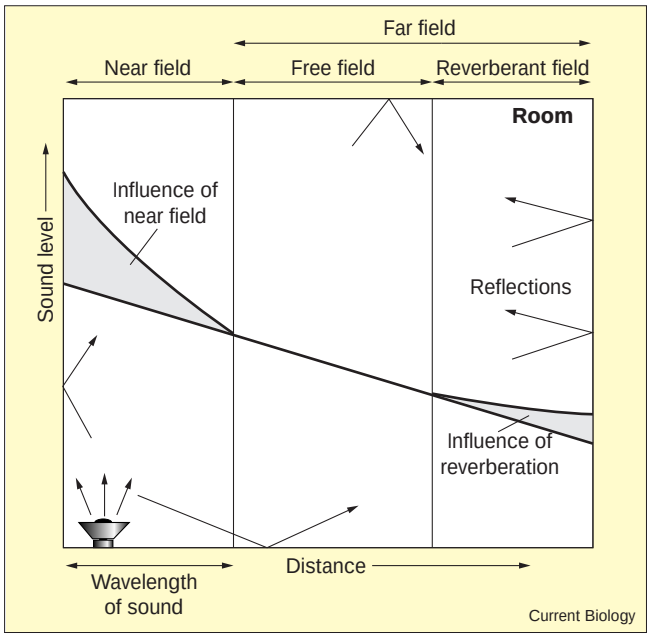
In addition to the classic cues of interaural time and level differences, sound localization in the horizontal and vertical planes — 'direction perception' — is known to depend on spectral cues provided by the directional filtering of higher frequency sounds by the body, head and, particularly, the outer ear (Figure 1). Sound direction perception is very accurate in open environments (the 'free field') and in the artificial, but acoustically simple, environment of an anechoic room, in which the walls are lined with sound absorbing material. For some sounds, however, direction

Figure 1



Sound localization cues. (a) Binaural cues of interaural time and level difference are produced by the extra time taken for sound to reach the far ear over the near ear (interaural time delay), and the sound shadow of the far ear due to the presence of the head (interaural level difference). (b) Convolutions of the outer ear impose direction-dependent shaping, measured at the eardrum, of the spectrum of a sound. These filtering effects will also contribute to the interaural level difference.

Figure 2



At locations near a sound source (left), or near the walls of a reverberant room (right), sound levels are variable and do not follow the normal, free field rule of decrease with the inverse square of distance. The grey areas on the graph represent the variable influences of the near field and reverberation.

judgements are poorer in complex, reverberant environments, such as rooms with reflecting walls [5]. In contrast, distance perception of an unfamiliar sound is not particularly good in the free field — at distances greater than the sound's longest wavelength (Figure 2) — because it is largely determined by, and therefore confounded with, the level (loudness) of the sound [6]. Other cues for distance perception are also available, however, and in an enclosed room, absolute distance judgements can be made using reverberation cues that are based on the proportion of sound energy reaching the ears directly from the sound source to that reflected by the sides of the room [7,8].

The recent development of technology for producing virtual space sounds — in which the cues provided by the head, the ears and the room are measured, digitally synthesized and mixed with the acoustic characteristics of the presenting headphones — has enabled the independent manipulation of the various cues, greatly enhancing our ability to study their relative contributions to spatial hearing. The listeners tested by Bronkhorst and Houtgast [3] could not distinguish such virtual sounds from real sounds presented within rooms by distant loudspeakers. The authors found that their listeners' virtual sound distance judgements were impaired when either the number or the level of the 'reflected' parts of the sound were changed.

The ratio of direct-to-reverberant sound energy did not tell the whole story, however. To fit their data accurately, Bronkhorst and Houtgast [3] developed a model in which the energy in the 'direct' sound was passed through a temporal integration window, the parameters of which were fitted to the experimental results. The best fit temporal window turned out to have a duration (6 milliseconds) that agrees closely with other estimates of auditory temporal processing [9,10]. The authors are careful to point out that distance perception, whether in real or virtual environments, is not static, but is dependent on the listener's adaptation to the sound source and the acoustical properties of the room. A term representing this 'learning' effect was factored into the model.

Neural encoding of sound source distance

Neurophysiological studies with a range of species have shown that neurons throughout the central auditory pathway tend to be tuned, to a greater or lesser extent, to the direction of a sound source [11]. The clearest evidence for neuronal selectivity for sound source distance has been found with echolocating bats. They navigate by emitting ultrasonic pulses of sound and listening for echoes due to reflections from objects in the animal's flight path. Whereas conventional auditory localization cues are used for directional hearing, bats can determine target distance from the time delay between the emitted pulse of sound and its returning echo. Neurons tuned to the delay between pairs of sounds that simulate the biosonar signals and their echoes have been described at various levels of the bat's auditory system and, in a 'range-finding' area of the cortex, are organized to form a neural map of echo delay and therefore of target distance [12]. In the bat's superior colliculus, a midbrain nucleus involved in the control of orienting responses to novel sensory stimuli, some auditory neurons are sensitive both to echo delay and the direction of the target, which is therefore represented in three dimensions [13].

The mammalian superior colliculus is of further interest in this respect, because the activity of its multisensory neurons can be enhanced or suppressed when stimuli of different sensory modalities are presented in combination [14]. In particular, the nature and magnitude of these interactions depend on the relative timing of the signals. For visual–auditory neurons, the largest response enhancements are often observed when the auditory stimulus is delayed with respect to the visual stimulus, a consequence of the difference in the time course of the transduction mechanisms for these two sensory systems. Because of the difference between the velocities of light and sound, this optimal inter-stimulus interval can be achieved naturally and corresponds to a particular distance from the animal's head [15].

There is much less evidence for distance tuning in the auditory system of non-echolocating animals. This dimension of

auditory space has been largely ignored because most free-field, neurophysiological studies of sound localization have used fixed arrays of loudspeakers or motorized hoop systems in which the direction, but not the distance, of a single speaker is varied with respect to the animal's head. Graziano *et al.* [4] have taken the natural next step of examining how the responses of auditory neurons vary with the distance, as well as the angular direction, of a sound source. They recorded from neurons in the monkey's ventral premotor cortex which, like the superior colliculus, is a multisensory area involved in the sensory guidance of movement. They had previously demonstrated that many neurons in the ventral premotor cortex respond to both visual and tactile stimulation. Although large in terms of their directional coordinates, the visual receptive fields in the ventral premotor cortex rarely extend beyond 30 cm from the head, and are therefore restricted to a region of space within the monkey's reach [16]. In their most recent study, Graziano *et al.* [4] have shown that the auditory receptive fields of ventral premotor cortex neurons exhibit similar properties.

The acoustically-responsive neurons showed some tuning for sound azimuth, although this was assessed on the basis of only six loudspeaker positions. Of greater interest was their finding that about 60% of these neurons responded more strongly to broadband sounds positioned 10 cm from the head compared to those at distances of 30 cm or 50 cm. In some cases, this can probably be explained, at least in part, by the dependence of the response on stimulus level. Other cells, however, showed little effect of stimulus level even though the magnitude of their responses varied significantly with stimulus distance.

Graziano *et al.* [4] found that the great majority of the acoustically-responsive neurons in the ventral premotor cortex also responded to visual and tactile stimulation. Multisensory neurons throughout the brain tend to have large, overlapping receptive fields for the different stimuli to which they respond. Whilst this makes good sense for the integration of information in the auditory and visual modalities, which are both concerned with detecting distant events, the significance of registration with receptive fields on the body surface is less clear. In the case of ventral premotor cortex neurons, however, sensitivity to tactile as well as to nearby visual and auditory stimuli would appear to be consistent with the likely role of this cortical field in the control of head and arm movements toward or away from stimuli in the vicinity of the animal's body [16].

Basis for auditory distance representation in the cortex

It is tempting to suggest that the model for sound distance perception in humans proposed by Bronkhorst and Houtgast [3] may be applicable to the responses of cortical neurons to real sounds presented by Graziano *et al.* [4]. There is, however, a fundamental difference in the way that auditory distance was examined in the two studies. The virtual space stimuli used by Bronkhurst and Houtgast [3] simulated source distances of a metre or more; this is what is known as the far field (Figure 2) and refers to the region of space within which both monaural and binaural cue values are essentially independent of distance. In contrast, the distances at which sounds were presented in the study by Graziano *et al.* [4] fall within the near field, a more complex region within which energy circulates without propagating [17]. Monaural spectral cues and interaural level differences associated with near-field sound sources therefore vary with distance [6,18,19], providing a possible basis for distance discrimination by both individual neurons and human listeners. This is obviously useful for localizing nearby sounds, but leaves unanswered the question of whether auditory neurons in the brains of non-echolocating mammals are sensitive to other cues, such as those described by Bronkhurst and Houtgast [3], which are available for more distant sound sources.

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